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A Haptic-Assisted Guidance System for Navigating Volumetric Data Sets

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Abstract

In this paper, a new approach for navigation assistance through sets of volumetric data is presented. This innovative method uses force feedback in two dimensions to guide the user to a region of interest. The haptic feedback is calculated under two methods and we explain the implementation of both approaches. The output is displayed by the Proactive Desk, a two dimensional force feedback device developed at the Advanced Telecommunications Research Institute. This new approach is targeted to scientists who work with sets of volumetric data and who wish to find information using visual scanning enhanced with haptics. Our system is designed for Magnetic Resonance Images (MRI) overlaid with functional MRI.

1. Introduction

Visualization of data has always been an important subject in the representation of information. It provides a fast way to localize data that could be important for the user. For the past two decades, data has become so complex and varied that a three dimensional representation is necessary. With the visualization of fluid dynamics, texture, and medical images, the field has broadened within the computational era. As noted by Lundin *et al*. [9], when working on medical data, analysis can benefit from the use of haptic feedback and the task execution speed is increased. In the article by Haan *et al*. [5], the authors note that even though people are used to working in the three dimensions of the real world, when performing tasks like drawing or measuring, they usually search for a supporting plane of reference.

In addition to the representation of the data, localization of specific data is a problem itself. In three-dimensional representations, occlusion is a common problem. This problem occurs when two or more objects overlap in the line of sight of the user, and the closest object occludes those farther away. This is, therefore, a common issue in three-dimensional visualization of medical data.

The use of Magnetic Resonance Imaging (MRI) and Functional MRI (fMRI) has increased over the past decade. fMRI is used to locate regions where activity of the brain is detected. These regions are of high interest to researchers and are a common subject of study. This activity is displayed to the user visually by overlapping the functional scan on top of the base MRI. An example of the problem of occlusion is shown in Figure 1. As seen in the figure, brain tissue is occluded by the overlapping of the fMRI. It is our intention to provide new ways of localizing information than by only providing visual cues.

Occlusion can be solved by the use of semi-transparent objects as noted by Iwata and Noma [8], however, multiple objects may overlap in the image. Moreover, the area of interest may not be large enough for the user to easily spot it.

In our current work, a new approach for navigation is presented. Our research is focused on the task of finding regions of interest over sets of volumetric data. The solution presented uses force feedback to guide the user's hand towards the region of interest.

The device for the display of force feedback that we use is the Proactive Desk (PD) by Noma *et al*. [10]. The PD is especially suitable for this project for the relatively large area that it can cover compared to other devices. Also, an important fact is that it works over a two-dimensional plane. Two methods for haptic rendering were developed and we will explain the implementation of these in the following sections.

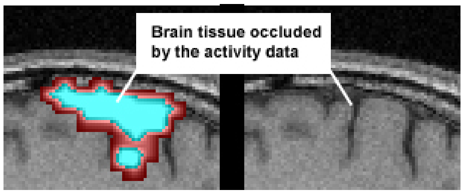

Figure 1: An example of the problem of occlusion of fMRI data overlaid on an MRI scan.

2. Related Work

Several approaches for volumetric representation by haptics (haptization) have been developed. The first method for haptization of volumetric data was introduced by Iwata and Noma [8]. Subjects were given the task of finding regions of “high density data” by providing them with visual and haptic feedback. Results showed in this task, that haptic feedback increased the accuracy of the subjects. The rate of error decreased from 35% in the visual treatment, to 19% in the visual+haptic treatment. In the study by Iwata and Noma, the user was always presented with visual information. No haptic guidance assistance was provided.

More recently Ikits *et al.*, from the University of Utah, introduced an algorithm that restricts the motion of a proxy in certain directions when working on volumetric data [7]. The goal of this research was to help the user to explore the volume. The haptized data used was heart muscle and brain tissue. However, no work was done in guiding the user towards specific data, for example, a brain tumor.

Reimersdahl *et al*. introduced rendering techniques for the exploration of Computational Fluid Dynamics data in virtual environments [13]. In this work a similar approach to one of our haptic rendering methods was used. In their gravity scalars method, points in the data grid are assigned a mass. This will attract the probe object to those regions of high density; however, this work uses a different haptic device, a PHANToM.

Linear trajectories for paths from outside the head to a target inside the brain were implemented by Hinckley *et al*. [6]. Here the user holds a prop that acts as the cutting plane of the data set, however, no active haptic feedback is given to the user. Moreover, no guidance assistance is provided.

Navigation and manipulation of 2D and 3D data have been tried before, and an excellent approach is that of Aliakseyeu *et al*. [1]. In this research a two-dimensional desk is provided to the user, where he is able to manipulate the data. The goal of the research was the exploration of three dimensional datasets. Informal results showed that the system added value in the task performance. However, again, no active haptic feedback was provided to the user.

At the University of Delft, Haan *et al*., created another approach for volume exploration employing passive feedback using a pad and a stylus [5]. This work is a good approach for volume slicing. In their research, however, the user tries to get an insight of the data by inspecting or probing the various data values. They do not provide any active force feedback for navigation.

Some techniques deal with the haptization of the information, static or dynamic, while other techniques deal with the restriction of movement of the proxy. Few techniques have worked on the task of finding information by navigation assistance.

3. The Haptic Feedback Device

The Proactive Desk [10] is a force feedback device that works by applying forces to electro-conductive objects over its surface, the desk (Figure 2). A projector, placed above this desk, is used to display images on its surface. The user can now feel haptic forces and, at the same time, see an image that correlates with the forces that he feels. The PD has its region of effect in the center of the desk of dimensions equivalent to a 512x512 square of pixels. Therefore, we present the image of the sliced data in the center and of exactly the same dimensions. The rest of the surface is used to support non-haptic interface widgets.

Our system uses a stylus for the navigation aid. The stylus we use has an aluminum disk attached to its tip. The color of this disk matches the color of the surface of the PD. By doing this, the projected image blends and the user can perceive only minor distortion. This stylus sits on top of the PD’s surface and it will move according to the forces applied by the PD. By holding the stylus in his hand, the user can feel sensations such as boundaries, viscosity, or forces which, in our case, are used for guidance. On the upper right corner of Figure 2 is a picture of the stylus with the aluminum disk attached to its tip.

The stylus is a wireless prop; therefore, its position has to be recognized by an optical sensor also positioned above the desk. The stylus position is transformed to mouse coordinates which are used to guide a computed probe object. Given the position of this probe we use the appropriate force that the PD will apply to the stylus.

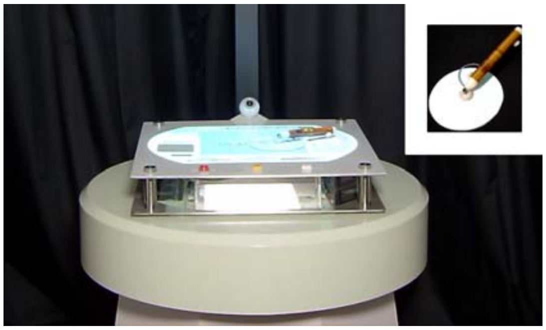

Figure 2: The Proactive Desk. On the upper right corner, we also present a picture of the stylus.

4. Guidance System

We present a solution to the problem of localizing data by using, as an example, overlapped fMRI data. Information of activity in the brain is obtained by giving stimuli while performing an MRI scan. We define our Regions of Interest (ROI) as those regions where activity was detected by the fMRI. Our research presents the implementation of a system capable of guiding the user towards the ROI depending on the distance to the region, or the distance and density of the target region. This system uses haptic feedback to push the user towards the desired direction. We calculate vectors that will provide us with the amount of force and direction necessary to guide the user. It should be noted that this technique should be applicable to other volume data sets as well, such as those used in the petroleum industry.

The force vectors are pre-computed and stored in a Force Vector Mesh (FVM). The system recognizes the two-dimensional position of the stylus and maps it to the three-dimensional volume. Once knowing this position, the system only performs a lookup in the stored FVM. With the resulting force vector, the PD can now guide the user in the necessary direction. A special case occurs when the target is on a parallel plane. We are currently dealing with ways of solving this situation.

Our system is capable of slicing the volume in any arbitrary position and orientation. Four planes are provided for this task: three orthogonal, axis-aligned planes, and one of arbitrary position and orientation. Any of the four may be chosen for navigation.

Aliakseyeu *et al.* incorporate the idea of "naturalness" by defining five guidelines that an interaction device should follow [1]. Our system complies with these five guidelines and, in addition, we provide haptic-assistance to help the user on the navigation task. This can be thought of as a merging of the ideas of Lundin *et al.* [9] and Aliakseyeu *et al.* [1].

4.1. System Overview

An image of the system we have developed is presented in the Figure 3. The ROIs are marked in green and blue in the center image. This center image is where the force vectors will be applied. While the user has the stylus in this area, he will be able to feel the PD guiding him towards the desired direction.

As mentioned before, there are four planes that are used to slice the data: three orthogonal, axes aligned planes and a fourth that we call the arbitrary cutting plane. This arbitrary plane lies fixed on a virtual floor. When transformations are applied to the data, such as rotations or translations, they will affect the way the plane intersects the data. The user can move the orthogonal planes by physical dials that we provide on the bottom of the PD, or by using widgets on the right-hand side of the work space.

As seen in the figure, we present a high-resolution, 512x512 pixel area in the center of the workspace. This is where the main display of information occurs, and this is also the area of effect of the PD. Since we give four different planes, we also provide a way of selecting one of these by widgets or buttons on the trackball described later in this section.

On the left-hand side of the PD, a three-dimensional representation of the MRI and fMRI data is presented as a wire frame. The orthogonal cutting planes are shown in gray. The arbitrary cutting plane is shown as the gray semi-transparent floor.

Manipulations of the wire frame such as rotations or translations are done by a trackball. The user can reorient the data by moving the sphere of the device. By doing this, the arbitrary plane that acts as a floor will cut the data in different orientations. The system provides widgets for these tasks that can be accessed by the stylus. The trackball is intended as a gross manipulation method by the non-dominant hand of the user. Finer manipulation, in this case guidance, will be provided to the dominant hand while the user holds the stylus. This follows the two-handed interaction work defined by Guiard [4].

It is our goal to guide the user to the ROI even if this is not visible. The user, therefore, can hide the fMRI data. The user is also capable of turning on and off the navigation aid. Some subjects may prefer the aid to be of a constant speed instead of increasing when closer to the ROI. An option where the user can normalize the vectors is also presented. The maximum force applied to the stylus is also configurable.

The system shows a low-resolution display of the three orthogonal and the arbitrary slices, as can be seen on the bottom of the Figure 3. The user is also presented with a glyph of the force vector that is currently applied to the stylus.

The MRI and fMRI data were provided in DICOM format. The fMRI was scanned while giving visual stimuli to the subject. There were 191 images of each set, each at a 256x256 resolution. The result was volume size of 191x256x256 cubic voxels. These dimensions correspond to the three volumes, the base MRI, the fMRI and the FVM.

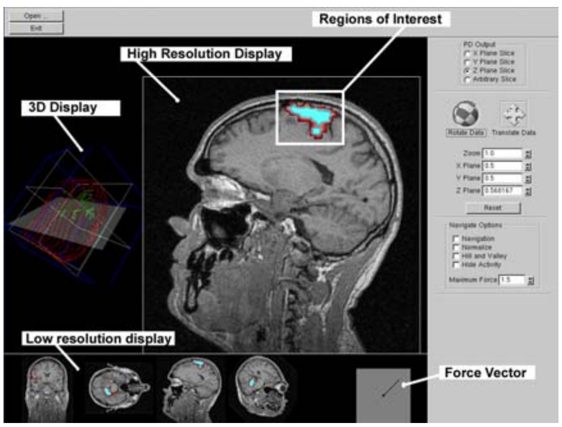

Figure 3: An example of how the system looks. We highlight the main tools provided to the user.

5. Haptic Rendering Methods

To display the appropriate force to the stylus, a FVM based on the fMRI data, is generated. Therefore, the dimension of this Mesh is also 191x256x256. The FVM can be generated under various methods. Next, we present the two developed under our current implementation. Each FVM was generated offline and saved to a file, since both methods require considerable computational power. We have to generate the FVM for each method of the fMRI before using it in our system.

We consider a ROI as a group of Points of Interest (POI). Each POI corresponds to one voxel in the fMRI volume. Both methods use an inverse distance function to modify the magnitude of the force.

The magnitude of the resulting force vector needs to be mapped to an amount of force that the PD can apply. We use a linear mapping to normalize the maximum force in the FVM to the maximum force the PD can generate. Alternatively splines and other types of curves could also be implemented.

5.1. Inverse Distance Function

The inverse distance function on every method was calculated by the following formula:

$$g(x) = \frac{1}{x^2}$$

By using this function, we ensure that the closer the voxel to the POI, the stronger the force of attraction will be.

5.2. Closest Point Method

This method calculates each force vector by taking the POI closest to the voxel and calculating a vector between these two. To determine the proximity, we use the geometric distance. Once choosing the vector, the magnitude will be modified to be equal to the normalized vector times the inverse distance function described earlier. This method can also be defined with the following formula:

$$\vec{F} = g(d) \cdot \frac{\vec{A}}{d}$$

where

$$\vec{A} = \{\min(\|\vec{V}\|) \mid \vec{V} = Pi - P; i = 0..n\}$$

$$d = \|\vec{A}\|$$

In this formula, *F* is the force vector, *g(x)* is the inverse distance function described earlier. *Pi* the ith point of interest; *P* the current voxel at which we want to calculate the force vector, *A* is the vector with the minimum magnitude of all the vectors from *P* to the point of interest *Pi*, and *d* is the magnitude of *A*. The value *n* is the number of points of interest. In this method we assume all the points to have the same intensity, we use this as the analogous of mass.

An example of how this method works is given in Figure 4. Black circles, labeled P1 to P4, are sample POIs, and circles in gray, labeled as A1 to A3, are sample positions for the probe object. Position A1 is obviously closer to P1 and therefore points towards it. Given the line formed by point P1 and P3, assume the x coordinate of position A2 is midway between the x coordinate of P1 and P3, but that the y coordinate of A2 is not aligned with these two points, but is higher up. By calculating the geometric distance, we find that A2 is pointing towards P2. As P1 and P3 are collinear, let’s assume the position A3 lies on this line and is midway between P1 and P3. When the position of the probe happens to be an equal distance from two or more POIs, the system will use the first calculated vector, in this case, the vector to P1.

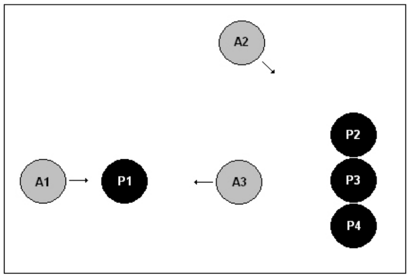

Figure 4: Example of the behavior of vectors with the Closest Point Method.

5.3. Sum of Attractions Method

The second method we provide is the Sum of Attractions. This method creates an FVM in which each vector is generated by the following formula:

$$\vec{F} = \sum_{i}^{n} Ii \cdot g(di) \cdot \frac{\vec{V}i}{di}$$

$$where$$

$$\vec{V}i = Pi - P$$

$$di = \|Pi - P\|$$

F is the force vector we are calculating; *Ii* the intensity at point *i*. *Pi* the ith point of interest; *P* the current voxel at which we want to calculate the force vector, and *di* is the distance between the two points, *Vi* is the vector between *Pi* and *P*, *g(x)* is the distance function described earlier. Again, the value *n* is the number of points of interest.

The resulting vector will be determined by the summation of the normalized vector formed by the current voxel and every POI, times the distance function evaluated on the magnitude of this vector before normalization, times the intensity of the point. Notice that this method is similar to a gravity model. The intensity of the point is analogous to the mass of the point

In Figure 5 we present an example of how this system works. We define a *region* as those points in close proximity with each other. The term *density* is used for the number of points in a region. The direction of the vector is not as obvious as in the previous method. Point A3 is pointing towards the region defined by P2, P3 and P4 because of its proximity and the fact that it is in a region of high density. Point A2 is pointing towards this same region even though it is closer to P1, because the region formed by P2, P3 and P4 is denser than P1. Point A1, however, is not pointing towards P2, P3 and P4 even though its density is higher, but because, geometrically, the distance to P1 is much shorter and therefore of more influence than the density.

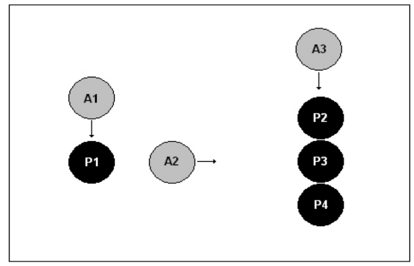

Figure 5: Example of the behavior of vectors with the Sum of Attractions Method.

6. Problems with the Current System

The generation of the FVM is a computationally expensive task, which is why it has to be pre-computed. For this reason, our system cannot handle dynamic changes in the data. Also, since our solution works on discrete space representing constant information, it is prone to aliasing artifacts.

Another important issue is the direction of the ROI when it lies on a parallel plane above or below the displayed plane in the data set. We are able to compute the direction to which the plane should be moved, however, an automatic option should be implemented. Two solutions are in progress right now. One solution will provide feedback to the user of "climbing up a hill" when the plane is somewhere in the data stack "above" the displayed plane, and "climbing down a valley" when the plane is "below." These types of haptic feedback have already been tested on the PD [14]. Another approach to solving this problem is by automatically moving the current plane towards the desired direction. Both of these solutions have straightforward implementations, however, the authors have decided to leave this as a future work.

7. Summary and Future Work

We have presented a technique for navigation on large sets of volumetric data using haptic feedback. Our approach provides a two-dimensional solution for the exploration of three dimensional data sets by using the Proactive Desk haptic feedback device. The current research is one of the first exploiting the advantages of this new device. One of the particular contributions of this work is the use of the user's natural understanding of information displayed on a flat surface.

To conduct subject studies to prove the usability of our system is an obvious next step. The first study in mind is to test the advantages of guiding the user over a flat surface towards a defined target. In this test we will also compare the two methods we used to create the FVM. A second study will include the full functionality of the system while moving the cutting plane in a three dimensional space. Analysis of the results of these studies will help us confirm whether our system provides a significant aid to the problem of localizing information.

The manipulation of the three-dimensional data is currently done with a trackball. However, better approaches for manipulation such as those by Hinckley *et al.* [6] or Fröhlich and Plate [3] may be implemented in the next version.

More techniques for generating the FVM will be researched in the next version of the project. The volume is currently examined pixel by pixel. Using an Octree may reduce storage requirements in empty areas, as noted by Avila *et al*. [2]. A custom-sized probe as that noted by Petersik *et al.* [12] may be tested instead of the point-based one we use.

Our current system provides a way of guiding the user to a ROI, however, no discussion was presented on haptically displaying these regions once reached. There are many approaches in solving this problem, such as that of Noma and Iwata [11]. We can implement other well-known techniques once our guidance approach is validated.

8. Acknowledgements

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